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AN EXPERIMENTAL DETERMINATION OF SUBATMOSPHERIC BURNING RATES AND CRITICAL DIAMETERS FOR AP/HTPB PROPELLANT

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DECEMBER 1988

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Measurements have been made of the burning rates of two formulations of AP/HTPB propellant in the pressure range of 0.3-1 atm. The experiments were performed in a windowed strand burner modified to operate under subatmospheric pressure conditions. Burning rates of the two formulations differ by almost a factor of two and the pressure dependence of both is well described by the usual power law function. Although 6.4 mm strands of the faster formulation burned stably down to 0.3 atm, it was found that the slower formulation strands would not burn stably even at 1 atm except in larger diameters. The critical diameter for self-extinguishment was found to increase with decreasing pressure.

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I. INTRODUCTION

The present work was undertaken in support of the M864 artillery round development. This round uses an AP/HTPB propellant in the projectile base to reduce base drag during flight. Subatmospheric burning rates, simulating operation at altitudes to 10 km, were desired to enable modeling of the drag reduction and consequent range enhancement. The propellant acts as a gas generator reducing the partial vacuum created at the projectile base in flight. The combustion gases escape the combustion chamber through an unchoked port in the projectile base. Ground tests of the base-section combustor in a spin fixture have also been conducted to measure the effects of spin rate on chamber pressure and combustion time. Similar tests in an altitude chamber are being planned. Apart from isolating the effects of spin and pressure on the combustion for modeling purposes, these experiments serve to trouble-shoot the combustion chamber sensors to be used in a later series of telemetered gun firings. This report describes only the results of the vacuum burning rate measurements. The spin tests are reported elsewhere.[1] As burning rates were the objective of this work, encounters with the low pressure deflagration limit were more of an experimental obstacle than a subject for study. Consequently, the data presented below on critical diameters is sparse. Since relatively little data of its kind appears to be available in the literature, it is included here.

II. EXPERIMENTAL PROCEDURES

The burning rate measurements were conducted in a windowed strand burner modified for vacuum operation. Figure 1 illustrates the setup schematically. The samples were burned cigarette fashion with an axial shroud of nitrogen gas helping to control smoke obscuration and inhibiting flamespread down the sides of the strand. The gas path is emphasized by the heavy lines in Figure 1. A constant nitrogen flow during the burn is obtained by maintaining a pressure of about 0.3 MPa upstream of a choked orifice using a standard pressure regulator. Flow rate can be selected by changing either the upstream pressure or the orifice diameter. The orifice itself consists of a sapphire watch jewel epoxied into a steel disk which is, in turn, conveniently captured in a Cajon VCO tubing fitting. Use of this type of watch jewel as a means of producing calibrated gas flows is discussed in Reference 2. The nitrogen flow thus produced is introduced to the combustion chamber through the sample mount which is configured to produce a uniform axial flow around the propellant strand. The combined nitrogen and combustion gases are drawn out of the top of the windowed chamber by a vacuum pump, whose suction is modulated by a vacuum pressure regulator. This regulator was designed and built at BRL for low pressure flat flame burner studies and is described in detail in Reference 3. Its operation can be understood from the schematic representation of it in Figure 1. Two opposing cylindrical nozzles, each with perforations on the tapered ends, are connected by a thin latex membrane (cut from a condom). This assembly is housed in a larger chamber which can be evacuated and bled back up to the desired chamber operation pressure, or "set" pressure. When the pressure in the combustion chamber exceeds the set pressure, the membrane expands exposing the chamber to suction from the vacuum pump through the perforations in the nozzles. When the pressure in the chamber falls below the set pressure, the membrane collapses and covers the perforations, effectively sealing the chamber off from the vacuum pump. Pressure generated in the chamber by the burning strand then raises the chamber pressure until the set point is reached. In operation the membrane oscillates between these two modes, providing pressure regulation in the chamber to within a few percent, as long as the gas generation rate is within limits which depend on the regulator's design. The regulator performed well for propellant strands with diameters less than about 8 mm. Since it became necessary to use larger samples, we attached a large surge tank to the chamber. With this larger effective chamber volume, pressure would rise slowly in the chamber but generally less than 10% during the course of a measurement. The pressure during an experiment is recorded with a digital oscilloscope from the analog output of a Baratron capacitance manometer. A typical record is shown in Figure 2.

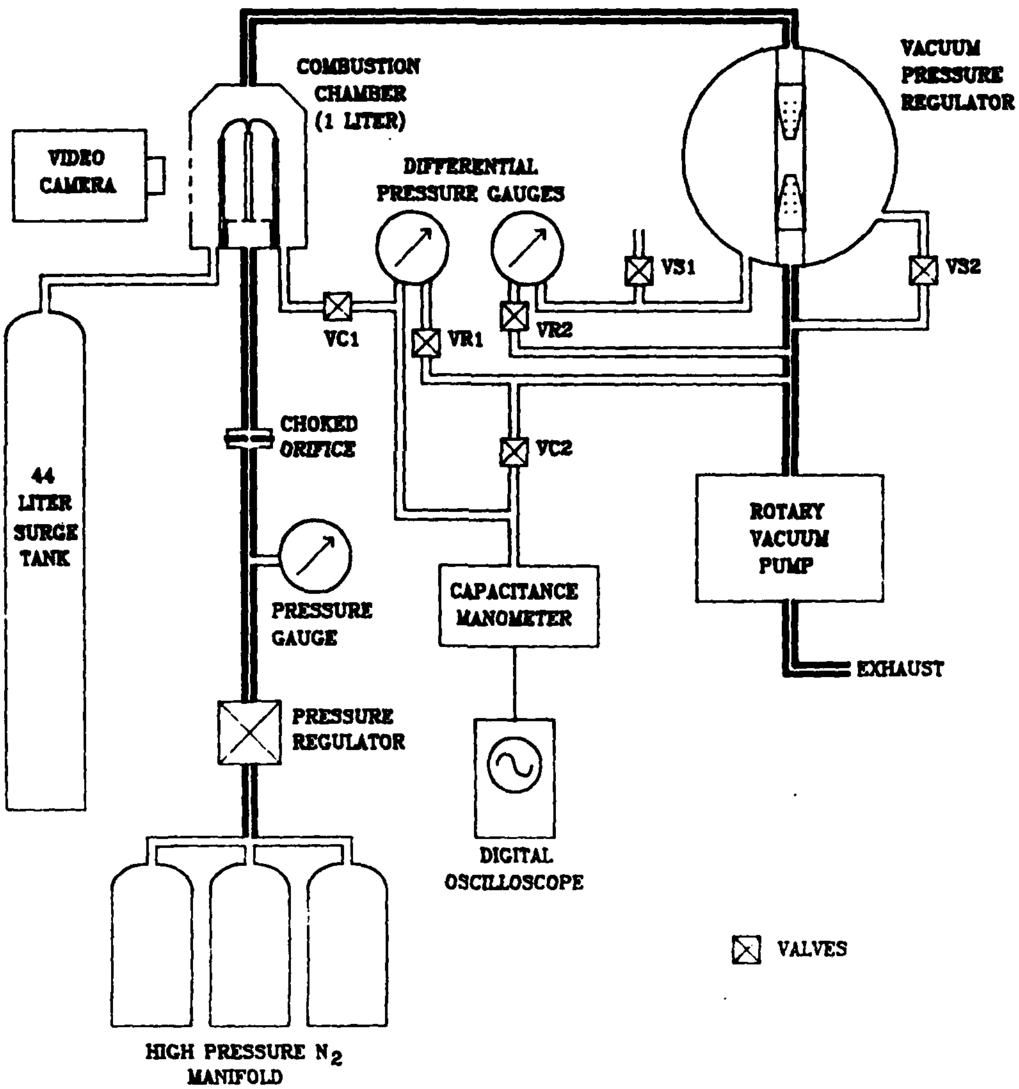

Figure 1. Schematic of Vacuum Strand Burner

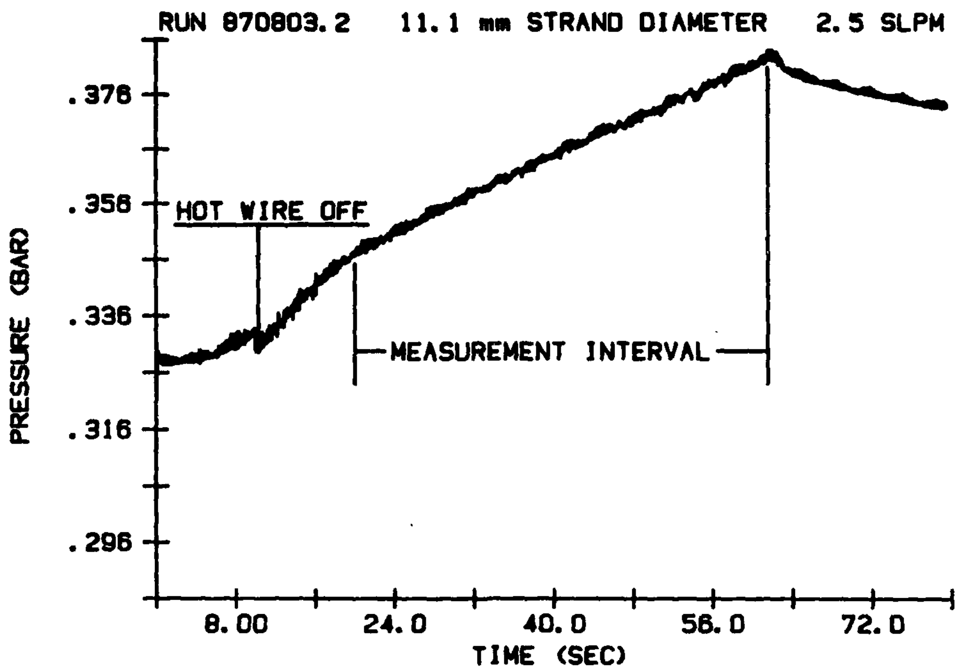

Figure 2. Chamber Pressure During Combustion of 11.1 mm Diameter Sample of AP-2 at 0.36 Bar and with Nitrogen Flow of 2.5 SLPM

Ignition of the propellant strand was accomplished by a resistively heated wire. At first nickel wire was used because it was readily available and had worked well with other propellants; however, its use resulted in frequent ignition failures because it would melt through before the strand was fully ignited. The use of tungsten wire obviated the ambiguity between ignition failure and extinguishment because it survived the flame temperatures and enhanced ignition of the sample by preheating the top end of the strand. The ignition stimulus was applied for 10 s, and this period was always excluded from the burning rate determination.

Combustion of the sample was video recorded by a system with both synchronized electronic strobe and shutter. The camera captures 60 fields per second and the strobe duration is 10 microseconds, so each field is temporally sharp. The video system is also equiped with a time code generator and X-Y coordinate digitizer, enabling almost continuous motion analysis capability. In practice, the video record for each strand was studied for periods of well-behaved planar surface regression, and some 20 points in this period were digitized for analysis. These displacements and times were then least-squares fitted to both first and second degree polynomials and the resulting plots compared. In most cases these two curves were indistinguishable, indicating a steady regression rate, and the slope of the linear curve accepted as the burning rate. If the two curves were judged sufficiently distinct, the run was discarded. The average pressure over the digitizing period was ascertained from the pressure record and associated with the computed burning rate.

III. RESULTS

Two propellant formulations were investigated. The first, designated AP-1 here, consists principally of 74% (by weight) ammonium perchlorate (AP), 15% hydroxy terminated polybutadiene (HTPB), and 6% oxamide. The AP component is trimodal, being made up of 40% 200 micron particles, 54% 14 micron particles, and 6% 7 micron particles. The second formulation, here termed AP-2, is the same except that 2% iron oxide replaces about 1% of the AP and 1% of the oxamide. Strands of AP-2 were prepared using cork borers of various diameters to core actual motor grains. AP-1 is a bit less resilient and tended to split with this method. Square strands of AP-1 were therefore cut with a heavy knife. Strands of both formulations were typically about 25 mm in length. AP-1 strands, about 6.4 mm on a side, were prepared and burned first in a fairly constant laboratory relative humidity of about 40%. No problems were encountered. AP-2 strands of 6.4 mm diameter, ignited by hot nickel wires in nitrogen, produced inconsistent results. The laboratory humidity during this time increased to 80-90%. To control this variable, AP-2 strands were routinely placed in a desicator for several days after preparation and before firing. A few tests were then done at a later time with samples conditioned in 100% relative humidity for comparison.

Because of the possibility of air diffusing into the base combustion section during projectile flight, experiments were done with both nitrogen and air as a purge gas. Atmospheric concentrations of oxygen are not likely to exist in the combustor, but the use of air in our strand burning tests would at least bracket the behavior. AP-1 burned with the same rate in air and nitrogen. In both gases the flame was a dull red and rather thin optically; little smoke was produced. In air the flame was slightly brighter and slightly less smoke was produced. In both gases many incandescent particles could be seen on the burning surface with no discernible difference due to the type of purge gas. AP-2 combustion was greatly affected by the use of air or nitrogen. In air the burning surface assumed a convex shape which became more pronounced with time, i.e., the burning rate at the edge was faster than at the center. The burning rate in air was some 25-50% faster than in nitrogen, depending on which feature one tracked on the strand. This suggested that oxygen from the purge gas participated in and enhanced the combustion. In air the flame was very bright and optically thick; little smoke was produced. In nitrogen the flame was the same dull red as with AP-1, but AP-2 produced copious amounts of smoke. Glowing particles were not evident on the burning surface of AP-2 in either air or nitrogen. In the former case such an observation could have been prevented by the brightness of the flame and in the latter by the dense smoke.

The bulk of the effort was spent on AP-2 combustion in nitrogen purge gas since this propellant formulation is the one in current use and the oxygen concentration in the projectile combustor is expected to be low. After the tungsten hot wire was discovered to give reliable ignition, the principal variable affecting the burn rate (apart from pressure) turned out to be the strand diameter. The greatest number of runs were performed at about 1 bar and the dependence of burning rate on diameter is shown in Figure 3. The data point at 6.4 mm represents three runs in which self-extinguishment occurred after successful ignition. In these cases the strand burned a distance of 8-12 mm before going out, and burning rates measured prior to extinction are given in Table 1. From these values it can be seen that whatever mechanism is responsible for the critical diameter deflagration limit, its effect on the burning rate is rather abrupt; i.e., if the sample burns at all, it burns at close to a fixed rate at a given pressure. Table 1 gives all of the data for AP-2. Although less data is available at lower pressures, it can be seen that the critical diameter increases as the pressure decreases. The trend is suggested in Figure 4.

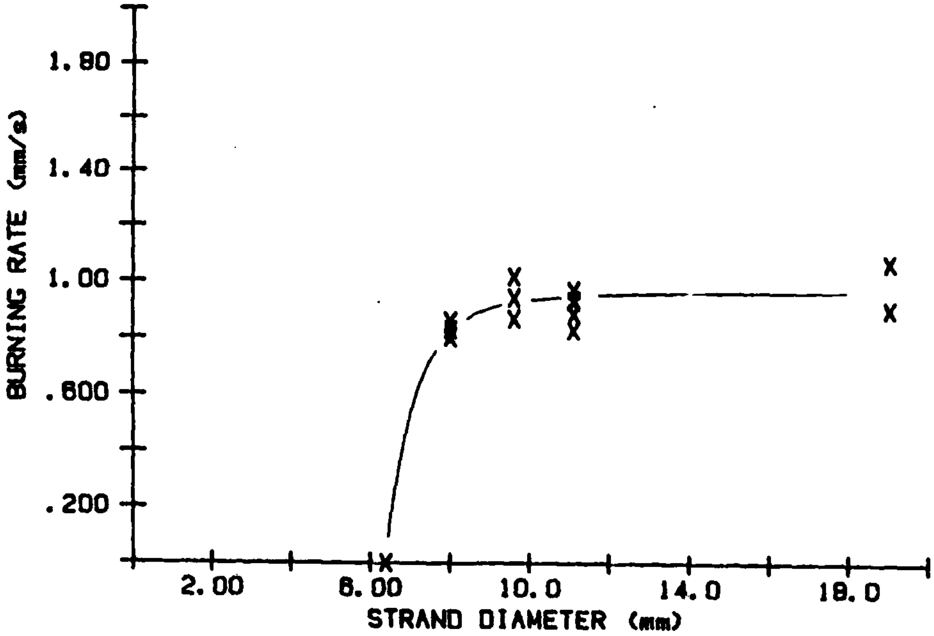

Figure 3. AP-2 Burning Rate vs. Diameter at 1 Bar

The purge flow rate was varied from 2.5 to 10 standard liters per minute (SLPM) to determine if it influenced the burning rates. As seen in Table 1, the burning rate was not sensibly affected; however, there is a suggestion that the extinction diameter increases with increasing flow rate. The geometry of the sample mount and chamber is such that the purge gas velocity by the sample is on the order of 1 cm/s for the above range in flow rates. Stronger flows might well have a more pronounced effect.

As mentioned previously, humidity was at first thought to be a factor in the burning rate, so samples were desicated prior to firing. To investigate this further, two samples were conditioned in a 100% relative humidity atmosphere for several days. These samples were burned at 0.36 and 1.1 bar. Surprisingly, no difference in burning rate was measured for these samples relative to the desicated ones. With the exception that the humid sample burned with somewhat more smoke, there was no difference in the appearance of the combustion. Helium pycnometer density measurements on a desicated sample and one exposed to lab air of >80% relative humidity yielded 1.532 g/cc and 1.718 g/cc, respectively. The higher density of the humid sample seemed to suggest the presence of microvoids in the propellant to which water molecules would migrate.

Table 1. Burning Rate Data for AP-2

PRESSURE (bar)	DIAMETER (mm)	N2 FLOW (slpm)	TEMPERATURE (C)	BURN RATE (mm/s)
1.06	19	10	NR	1.07
1.02	19	10	NR	0.904
1.06	11.1	2.5	24	0.928
1.05	11.1	2.5	22	0.930
1.05	11.1	5	27	0.969
0.95	11.1	5	NR	0.828
1.04	11.1	10	NR	0.885
0.98	11.1	10	NR	0.934
1.04	9.6	5	27	0.868
1.06	9.6	10	28	0.942
1.06	9.6	10	29	1.018
1.03	8.0	2.5	25	0.862
1.03	8.0	5	24	0.802
1.05	8.0	10	25	0.831
0.94	6.4	5	NR	0.790 X
0.94	6.4	5	NR	0.837 X
0.94	6.4	5	NR	0.773 X
0.691	11.1	2.5	24	0.737
0.698	11.1	2.5	25	0.664
0.661	11.1	5	24	0.700
0.654	9.6	5	25	0.676
0.667	9.6	10	25	0.703 X
0.658	8.0	2.5	25	0.620 X
0.348	11.1	2.5	24	0.488
0.363	11.1	2.5	23	0.461
0.343	11.1	5	24	0.440
0.333	11.1	5	25	0.450
0.335	9.6	5	25	0.436 X
0.336	8.0	2.5	25	0.417 X

NOTE: Runs marked with an X self-extinguished after burning about a cm. Burning rates are measured prior to extinction. NR means "not recorded".

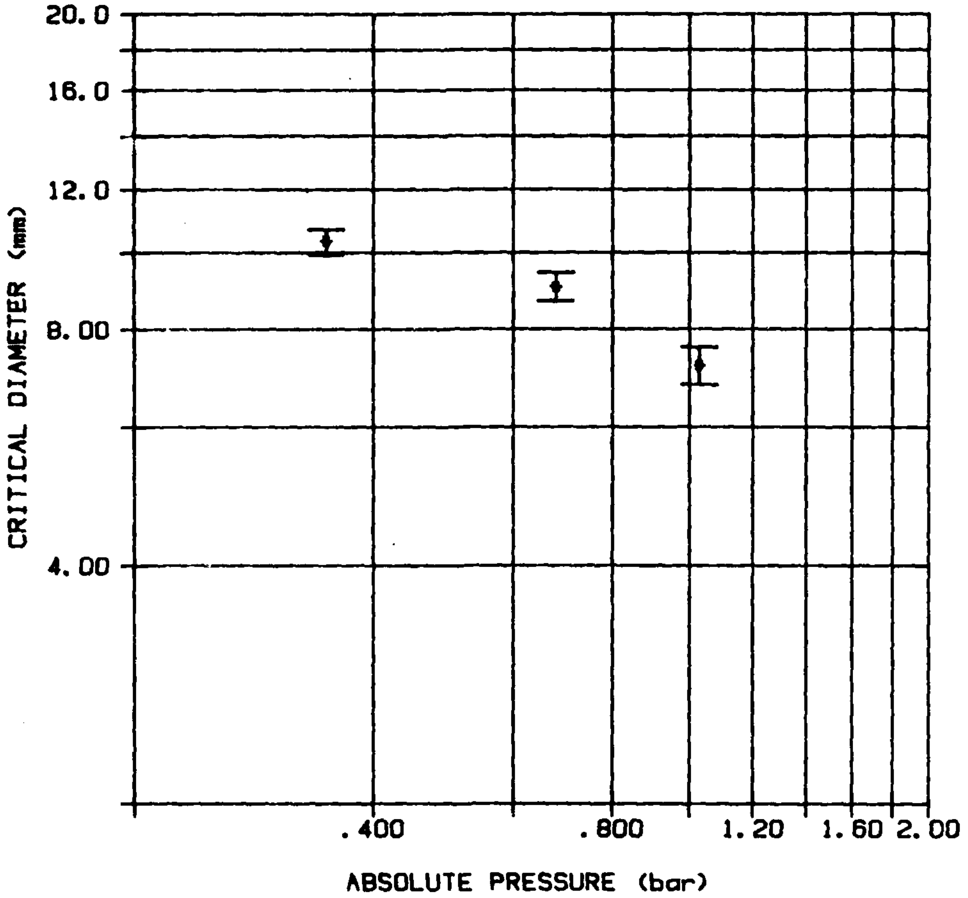

Figure 4. Critical Diameters for AP-2 Self-Extinguishment

IV. DISCUSSION OF CRITICAL DIAMETER OBSERVATIONS

Since the matter of critical diameters was incidental to our burning rate objective, the resulting precision and number of measurements are not optimum for a discussion of extinction phenomena. However, the measurements can be usefully related to previous work in the same vein. A brief literature search revealed much past discussion of the circumstances and causes of pressure deflagration limits for AP and AP propellants but few determinations of the critical diameter as a function of pressure at the low pressure limit.

The first and most extensive measurements (that we could find) were done by Cookson and Fenn[4] for AP propellants with a polyester binder. AP loadings of 78% and 80% were used with particle sizes 25 microns or less and 80 microns or less. In that work the pressure at which a square strand of given dimension self-extinguishes was determined by igniting the strand at higher pressures and carefully lowering the pressure until it went out, noting the pressure at which this happened. Reproducibility of a few percent was reported using this method. Consistent with our results, they found that strands of the faster-burning propellant (80% AP) extinguished at a lower pressure than strands of the same diameter in the slower formulation. Drawing a parallel between the heat loss effects leading to critical diameters in propellant strands and wall effects in flow through conduits, the reciprocal of the critical diameter (effective diameter for their square strands) was plotted vs. the corresponding extinguishing pressure. Plotted in this way, some two dozen data points fell on two straight lines, one for the 80% AP and one for the 78% AP propellants. The intercept on this plot for strands of infinite diameter occurred at finite values of pressure, presumed to be "the" low pressure deflagration limit for one-dimensional combustion. Plotting the reciprocal of critical diameter from our Figure 4 vs. pressure places the infinite diameter intercept for our data at negative pressures even taking the uncertainties of our go/no-go method into account. Neither does our data closely approximate a straight line, although this could be influenced by the paucity of data points.

Two possibilities could explain these conflicting findings. One is simply that the propellant used by Cookson and Fenn behaves differently. Steinz[5] compared burning rates vs. pressures at subatmospheric pressures for a wide variety of AP propellant binders. Both extinction pressures and pressure dependences in this range varied greatly among propellants with different binders. Another possibility is that the two methods of determining the critical diameter are not equivalent. Park, et al.,[6] made a careful study of the methodology of determining the low pressure deflagration limit. They found that in general the two methods do give differing values, with the magnitude of the discrepancy dependent on the binder type. The dynamic pressure method produced a lower extinguishment pressure than the go/no-go method for all of their propellants. No explanation for this behavior was apparent. It is also interesting to note that their critical diameters, determined by the dynamic method, when plotted as reciprocals vs. pressure did not fit well on a straight line as found by Cookson and Fenn, and if the best straight line was drawn, the infinite diameter intercept was at zero pressure, not a finite value. Thus, while the surface-to-volume ratio is likely to be an important parameter in the critical diameter extinction phenomenon, its linear dependence on extinguishing pressure is not an adequate universal description.

V. SUMMARY

Burning rates of two similar formulations of AP/HTPB propellant were measured at room temperature over the pressure range 0.35-1 atm. The data for both is depicted in Figure 5 along with non-linear least-squares fits to power law functions. It was found that strands with diameters smaller than a critical value would self-extinguish during burning. This critical diameter increases with decreasing pressure and probably with increasing purge flow rate. For a given pressure, the critical diameter is smaller for the propellant with the faster burning rate. Relative humidity of propellant storage environments did not affect the burning rate (of AP-2). Future plans are to measure the pressure dependence of the burning rate to lower pressures and over a range of ambient temperatures.

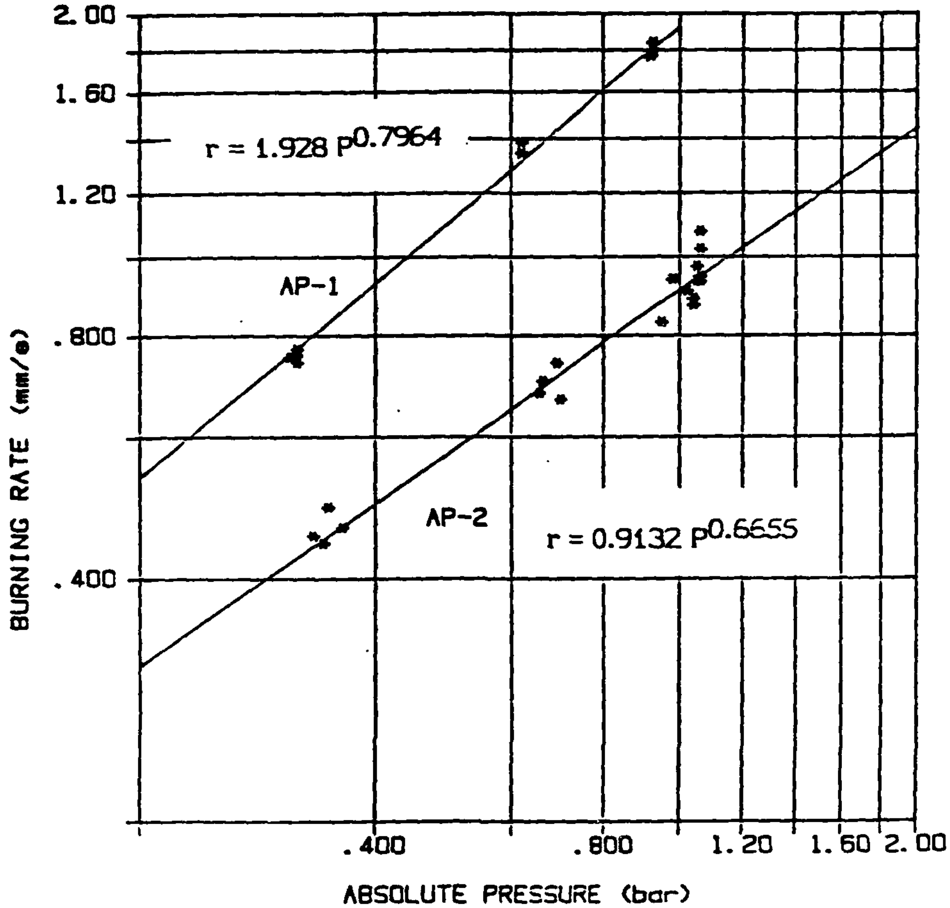

Figure 5. Experimental Burning Rates and Power Law Fits

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